Electronic Certificate

Field of the Invention

5   The present invention relates to electronic certificates that pass on (delegate) an attribute from an issuer to a subject and are signed by the issuer.

As used herein, the term "attribute" is used in a broad sense to include any capability, characteristic or authorisation that can be associated with the subject, this usage being

10   maintained even when discussing published documents that would themselves place a more restricted meaning on the term.

Furthermore, as regards to term "delegation" used herein to refer to the bestowing of an attribute by an issuer of a certificate to the subject named in the certificate, although in the

15   form of certificate discussed in detail below (SPKI certificate) the issuer has the right to exercise (as well as bestow) the attribute concerned both before and after bestowal of the attribute on the issuer, this is not necessarily true for all forms of certificate to which the present invention can be applied. Accordingly, the term "delegation" should not be read as implying anything about the issuer's right, or lack of right, to exercise the attribute being

20   bestowed on the subject.

Background of the Invention

By way of introduction, the general context and usage of SPKI certificates (which form part of the prior art) will first be described with reference to Figure 1-4 of the

25   accompanying drawings.

Figure 1 depicts a situation where a resource R has authorized party P_1 to use the resource - in effect, R has given access authorisation A to P_1. P_1 can thus contact R and use its capabilities, R allowing access to P_1 upon P_1 establishing its identity. In addition, R has

30   given P_1 the right to pass on ('delegate') the authorisation to others - in Figure 1, P_1 is shown as passing authorization A to party P_4. When P_4 contacts resource R, the latter will

require some proof that P_4 has indeed been authorised by P_1; this proof takes the form of a certificate C_{1-4} issued by P_1 to P_4 and provided by P_4 to R. In the electronic world this certificate will generally take the form of a digitally-signed document signed by P_1 using public-key / private-key cryptographic technology.

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For present purposes, it will be assumed that the certificate C_{1-4} (and the other certificates referred to below) are SPKI-like certificates, though it should be understood that this is not essential for the present invention. SPKI ("Simple Public Key Infrastructure") certificates are described detail in references [2],[3],[4] listed at the end of this description. Figure 2

10 illustrates the main elements of an SPKI-like attribute certificate (as already noted, the term "attribute" is herein used broadly and in relation to SPKI certificates encompasses both "authorization" and "attribute" certificates as defined in the above-referenced documents). The Figure 2 certificate has fields for specifying the issuer of the certificate (ISSUER), the beneficiary of the certificate (SUBJECT), the attribute being passed to the

15 subject by the certificate (AUTHORIZATION), whether onward delegation of the attribute is permitted (DELGATION), and the limits of validity of the certificate (VALIDITY). An important feature of SPKI-like certificates is that that they are primarily associated with principals that are public keys (or their hashes) rather than with parties identified by distinguished names. Thus, the "issuer" will always be a principal, that is, a public key or

20 its hash); similarly the "subject" can either be a principal or, as will be seen later, a name that can be translated by a name certificate into a principal. Of course, there will be a keyholder who controls the private key associated with the public key forming a principal - however, it is not fundamental that the keyholder is named .

25 In addition to the above-mentioned fields, certificate C_{1-4}carries a digital signature formed by using the private key of the issuer.

In relation to the Figure 1 example, P_1 would be keyholder for a first key pair and P_4 the keyholder for a second key pair, the "issuer" of the certificate C_{1-4} then being the public

30 key of the key pair associated with $P_1$and the "subject" being the public key associated with P_4. On receiving the certificate, R checks it by using the digital signature and public

key of the issuer. Since R will know the public key of P_1 and trust this knowledge (this would be part of the original authorisation of the P_1 by R), R can now be sure that the keyholder associated with the public key forming the subject of certificate C_{1-4} has been duly authorised by P_1. R can establish that the party requesting access (P_4) is this keyholder

5   by an appropriate challenge-response transaction (in which P_4 is required to use its private key to encrypt data sent by R, R then checking the returned encrypted data using the public key for which P_4 is supposedly the keyholder).

Figure 3 illustrates a more complicated situation in which P_4 receives authorization A from

10   P_1 not directly but through intermediate parties P_2 and P_3. This time P_4 has the following certificates:

C_{1-2}, - the certificate given by P_1 to P_2 to delegate authorisation A to P_2;

C_{2-3}, - the certificate given by P_2 to P_3 to delegate authorisation A to P_3;

C_{3-4}, - the certificate given by P_3 to P_4 to delegate authorisation A to P_4.

15   O f course, the parties P_1, P_2, P_3 and P_4 are not specified in the certificates directly, the latter referring to public keys K_{PUB1}, K_{PUB2}, K_{PUB3} and K_{PUB4} respectively associated with P_1, P_2, P_3, and P_4.

P_4 when requesting access to resource R passes the latter all three of the above certificates

20   which R checks; R also checks that the party requesting access (P_4) is the key holder of public key K_{PUB4}. Thereafter, R has the task of determining whether K_{PUB4} (P_4) has indeed been delegated authorisation A. In other words, R needs to be able to establish a trusted chain of delegations of authorisation A from itself to K_{PUB4}. The first link in this chain is, of course, the delegation by R to K_{PUB1} and R does not require a certificate to prove this - it is

25   a "trust assumption" of R. R can then see from certificate C_{1-2} that K_{PUB1} (P_1) has authorised a principal constituted by public key K_{PUB2} (P_2). From certificate C_{2-3}, R can also see that K_{PUB2} has in turn passed on the authorisation to K_{PUB3} (P_3); finally, C_{3-4} shows that K_{PUB3} has passed on authorisation A to K_{PUB4}. By combining the certificates, R can establish the required trust chain from itself to K_{PUB4} (P_4).

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In carrying out the above proof, R will also have checked that the "delegation" field of each of the certificates C_{1-2} and C_{2-3} permitted onward delegation of authorisation A. Additionally, the validity fields of all three certificates will have been checked.

5   It is possible that one party in the chain only delegated a subset of the authorisation A (for example, only some of the capabilities of R can be used by the subject of the certificate). R therefore needs to ascertain what is the scope of authorisation reaching K_{PUB4} (P_4) which is done by determining the intersection of the authorisation fields of all the certificates and seeing if this encompasses the requested access.

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As noted above, the "subject" of an SPKI-like certificate can be identified by a name rather than a principal; this name will be a local name referred to the name space in which it is defined (so as to provide a fully qualified SDSI name - see references [3] and [6]). The name space identifier starts with the public key of the "issuer" responsible for the space

15   within which the name exists (followed possibly by one or more sub-name spaces identified by name). Where a local name occurs in the "subject" of a certificate, the name space to which it refers is taken to be that of the "issuer" of the certificate. Naming a principal, if done, is primarily done for human convenience whilst SPKI processing systems fundamentally work with principals. The mapping between a name and the

20   corresponding principal is done using a name certificate. Figure 3 depicts an SPKI name certificate and, as can be seen, the certificate has four fields that specify the principal who is the issuer of the certificate (ISSUER), the name being assigned in the name space of the issuer(NAME), the subject being named (SUBJECT), and the validity limits of the certificate (VALIDITY).   The name certificate also carries a digital signature, formed

25   using the private key associated with the issuer.

In the most straightforward case, the subject will be a principal so that the certificate maps a name in the issuer's name space to a corresponding public key (or its hash) - this is the case illustrated in Figure 3 where the local name "name" that forms the content of the field

30   NAME is depicted as combining with the public key of the issuer K_{PUB_issuer} to map to the

public key $K_{PUB\_subject}$ in the SUBJECT field. The subject may, however, alternatively be a fully qualified SDSI name.

In determining whether a trust chain exists, it may be necessary to use a name certificate to
5   map an authorisation given to a named subject to the corresponding principal.

A more formal consideration of the combining together of contents of certificates is given in section 1 of the Appendix forming the final part of this description. In particular, section 1, Appendix A treats both the delegation rule for combining 5-tuples formed by the
10   contents of attribute certificates, and the naming rule for name mapping using 4-tuples formed by the contents of name certificates. The tuple representations used in the Appendix and at other places in this description are of the form:

5-tuple: $<i,s,a,d,v>$ where i, s, a, d, v respectively correspond to the issuer, subject, authorisation, delegation and validity fields of an attribute certificate, and

15   4-tuple: $<i.n=s,v>$ where i, n, s, v correspond to issuer, name, subject and validity of a name certificate.

(It will be appreciated that the corresponding graphical representations of certificate contents in the accompanying drawings are less formal, for example the contents of an attribute certificate are generally shown as an arrow from the issuer to the subject, omitting
20   the delegation and validity elements and, where required for clarity, also the authorisation element - which, if present, is placed alongside by the arrow).

Proving a trust chain from the contents of certificates is relatively straight forward if the proving engine is presented with the correct certificates (or, rather, their contents) in the
25   order required. However determining what certificates should be presented may not be a trivial task - it may be necessary to select the required certificates from hundreds of available ones. The task of choosing the certificates, sometimes referred to as "certificate path discovery", is discussed in the MIT Masters thesis of Jean-Emile Elien (reference[7]). A different form of discovery engine is described in this specification and forms the
30   subject matter of our co-pending UK patent application, of the same date, entitled "Method and Apparatus for Discovering a Trust Chain Imparting a Required Attribute to a Subject".

The present invention relates to the following issue. It is not uncommon in everyday life that bestowal of an attribute is conditional upon some other attribute - for example, membership of a professional association will generally depend upon the subject having certain academic qualifications. However, in the electronic world a certificates is generally

5   only issued once any prior conditions regarding the attribute to be possessed by the subject have been proved to the satisfaction of the certificate issuer. This can significantly hamper the issuing of certificates but is generally accepted as it is seen as part of the value being added by the certificate issuing authority.

10   It is an object of the present invention to provide an improved certificate infrastructure easing the issuing of certificates and increasing their flexibility.

Summary of the Invention

According to one aspect of the present invention, there is provided an electronic certificate

15   that has content data specifying an attribute delegation from an identified issuer to a certificate subject, and an electronic signature for confirming the content data; the content data including a condition requiring that a particular subject must have a particular attribute in order for the delegation to be valid. The said particular subject may be the same as or different from said certificate subject. The certificate subject can be specifically identified

20   in the content data or may be unspecified whereby the attribute is delegated to any subject capable of showing the certificate to be satisfied. More than one such subject-directed condition can be included in the certificate, the conditions being combined in a predetermined logical relationship.

25   The present invention also contemplates methods and apparatus for generating and using such certificates.

Of course, the standard VALIDITY field of prior art certificates is, in effect a condition carried by the certificate. By way of example, the VALIDITY field of an SPKI certificate

30   will contain data about one or more of the following:

    -   a date range identifying the period over which the certificate is valid;

- the location of a certificate revocation list that should be checked before the certificate is used;

- the location where a one-time use permission can be obtained or the certificate re-validated.

5   As can be seen, the VALIDITY field of an SPKI certificate acts as a condition directed at the validity of certificate itself and this is how it is generally perceived by persons skilled in the art. The VALIDITY field does not define an attribute required of a particular subject.

10   **Brief Description of the Drawings**

A certificate embodying the present invention and a trust chain discovery engine adapted to use such a certificate will now be described, by way of non-limiting example, with reference to the accompanying diagrammatic drawings, in which:

. **Figure 1**   is a diagram depicting a simple authorisation delegation;

15   . **Figure 2**   is a diagram of an attribute certificate;

. **Figure 3**   is a diagram depicting an authorisation delegation chain and the role of certificates in proving the chain;

. **Figure 4**   is a diagram of a name certificate;

. **Figure 5**   is a diagram illustrating the form of a conditional certificate embodying the

20   present invention;

. **Figure 6**   is a diagram of a trust-chain discovery engine;

. **Figure 7**   is a diagram depicting a delegation chain forming the basis of a first example to be proved by the Figure 6 engine;

. **Figure 8**   is a table illustrating how the Figure 6 engine proves a trust chain for the

25   first example;

. **Figure 9**   is a diagram depicting a delegation chain forming the basis of a second example to be proved by the Figure 6 engine;

. **Figure 10**   is a table illustrating how the Figure 6 engine proves a trust chain for the second example;

30   . **Figure 11**   is a diagram illustrating the incorporation of the Figure 6 engine in a resource subject of access requests;

Best Mode of Carrying Out the Invention

Figure 5 shows a certificate embodying the present invention. The certificate is of the same general form as the attribute certificate shown in Figure 2 but now the Validity field includes a subject-directed condition 40 in addition to the normal date/non-revocation/permission validity conditions placed on the certificate itself. The condition 40 could alternatively be included in a different field or its own field. The condition 40 reads (IF "XYZ") which is interpreted to mean that some attribute "PQR" must be true in respect of the subject of the certificate before that subject can be taken as having been delegated the attribute specified in the Delegation field of the certificate.. Certificates including such subject-directed conditions are referred to below as 'conditional certificates'.

More than one subject-directed condition can be included in a conditional certificate, most readily with an (implied or explicit) AND relationship between the conditions. Conditions may, however, also be linked by any other logical operator, though apart from AND, only the OR and NOT operators are likely to be of significant use (with regard to a negated condition, this of course means that the negative has to be positively proved).

Conditional certificates can usefully be employed, for example, to localize a privilege. For example, an employee may only be authorised access to a particular resource from a given network subnet - this can be achieved by placing a subnet condition in the certificate giving resource access rights. The resource, in seeking to verify that the employee has access authorisation, now needs to verify not only that the basic access authorisation attribute stems from a trusted source, but also that the employee has the specified subnet location based on trusted information.

For the Figure 5 certificate, the subject of the condition 40 was implicitly the same as the subject of the certificate as a whole. This could be the only possibility permitted for a particular type of conditional certificate; however, it is also possible to require that the subject of the condition must be explicitly declared, or to specify that if a subject is given

5 in the condition then this should overrule a default assumption that the subject of the condition is the same as the subject of the certificate. Where provision is made for the subject of the condition to be specified, then it becomes possible for the subject of the condition to be different to the subject identified in the SUBJECT field of the certificate.

10 It is also possible to issue a conditional certificate with no subject identified in the SUBJECT field in which case the attribute associated with the certificate will be conferred on any subject meeting the specified condition(s).

It will be appreciated that appropriate methods and apparatus for generating conditional

15 certificates are well within the competence of persons skilled in the relevant art.

As will be more fully described hereinafter with reference to Figure 13, where a conditional certificate is involved in proving a trust relationship, the condition (or conditions) in the certificate effectively gives rise to another trust relationship to be proved

20 - in other words, it creates a branch in the trust chain being built. Provided the reduction engine being used to verify the trust relationship is aware of this possibility, branched trust chains can be handled without undue complexity being added to the basic reduction engine. Thus, in one arrangement, the justifying certificates are presented to the reduction engine in forward (or, indeed, reverse) order, starting with the main branch followed by

25 each other branch in turn. The reduction engine entity can then readily reduce the first set of certificates, using the delegation and naming rules, to establish the trust relationship represented by the main chain, noting on the way any conditional certificates and the required trust relationship they demand. The remaining certificates are then used to establish any such additional trust relationships.

30

As regards discovery engines for finding the set of certificates required to prove a trust

relationship, these can also be arranged to handle conditional certificates by recognizing that a new trust chain branch must be established for each condition attached to a certificate used in building the chain. This is true regardless of whether the discovery engine works forwards or backwards to prove the trust relationship. A discovery engine

5   that performs a backwards proof and which is capable of handling conditional certificates will now be described, starting with a description of how the trust engine operates in processing ordinary (non-conditional) certificates.

Trust Chain Discovery Engine

10   The trust-chain discovery engine 50 illustrated in Figure 6 operates to seek to find a trust chain that starts with a trusted issuer and ends with a specified subject 51, and delegates at least a particular attribute 52 to that subject. In seeking this trust chain, the engine 50 uses axioms (trust assumptions) 53 that specify trusted issuer(s) and/or trusted delegation(s) involving a trusted issuer, and premises 54 formed by the contents

15   (5-tuples and 4-tuples) of attribute and name certificates 55 which have been presented at some stage to the engine 50. These certificates are checked by a certificate verifier 57using for each certificate the accompanying signature and the public key of the issuer; although Figure 5 depicts the certificates as being checked when presented, this checking could, in fact, be left until after the certificate has been found to be involved

20   in establishing a trust chain of interest.

The trusted issuer may be a specifically identified principal or, more typically, the discovery method itself (labeled "SELF" below) - this latter possibility is useful as it enables principals that are inherently trusted to be specified in the same format as the

25   certificate-based premises with the issuer being SELF and the subject being the trusted principal (the attribute thus delegated then corresponding to the field over which the principal is trusted). This commonality of format facilitates processing. Where the trusted issuer involved in a delegation expression is SELF, this can conveniently be represented by a null issuer (though for clarity in the following description, the label

30   "SELF" is retained). In the examples given in the following description, the trusted issuer is assumed to be SELF for simplicity.

It will be appreciated that the engine 50 can conveniently be implemented by appropriate programming of a general purpose computer and associated memory for storing, *inter alia*, the axioms, certificates and premises, and intermediate processing

5 results.

In general the discovery engine operates by starting not with the first link in the trust chain (an axiom / trusted delegation) but with the desired conclusion which it then tries to justify by a backwards proof process applying reverse forms of the delegation and

10 naming rules normally used for tuple reduction. Thus, a main processing functional block 59 of the discovery engine starts with a functional block 60 that forms a primary goal to be proved in the form of a 5-tuple:

<SELF, Subject 51, Required Attribute, *, true>

where "*" represents any valid value. In this respect, generally the state of the

15 delegation element does not matter - which is not the case at all for intermediate delegations.

Blocks 61 and 62 represent a recursive process of decomposing a goal to be proved into subgoals which then become the focus of the goal proving process. A goal (subgoal)

20 that does not have SELF as the specified issuer is considered proved if there is a matching premise whilst the subgoal including the issuer SELF is considered proved if there is a matching axiom.

Block 61 checks to see if the outstanding goal to be proved (always arranged to be the

25 goal including SELF as issuer) is proved by any of the axioms 53 - if it is, the primary goal has been proved and the chain of this axiom and the premises proving the primary goal is returned. However, if the goal containing is not matched by an axiom, block 62 is entered.

30 Block 62 seeks to decompose the outstanding goal into subgoals (usually just two).Subgoals are generated by using one of the certificate-derived premises (name or

attribute certificate) as one of the premises formed by a reverse application of the delegation or name rule. Thus, if the subject of the goal to be proved is "G" and the attribute concerned is "h", then the premises 54 are searched for a premise with subject also "G" and an attribute at least as embracing as "h". If such a premise is found, then this premise forms one of the new subgoals; the other new subgoal then has as its subject the issuer of the premise just found and used for the first new subgoal whilst the issuer of this second new subgoal is, of course, SELF. The attribute passed by the second subgoal is set to be the same as for the first new subgoal. The first new subgoal is justified immediately since it corresponds to a premise 54 and processing now returns to block 61 to check if the outstanding subgoal (the second newly created one) is proved by an axiom.

It may not be possible to decompose a particular goal to be proved into any of the premises, in which case the current chain being explored is not valid. In this case, processing backtracks towards the primary goal until it reaches a subgoal that can be decomposed by a different one of the premises to that previously used to decompose that subgoal. Assuming that such a re-decomposable subgoal exists, the processing continues in the manner already described. However, it may be that all possible decompositions have been tried without a complete chain back to SELF being discovered; in this case processing terminates with the primary goal unproved.

During processing, a careful track is kept (block 63) of what has been tried and what has not (that is, which premises have been tried against which subgoals) and what premises currently make up the chain being explored. This is to enable the backtracking to proceed in a structured manner and to permit the premises making up a successful chain to be returned.

It is conceivable that the proving process could loop which risks processing going on indefinitely. To avoid this, a subgoal list 64 is maintained of all subgoals created. Each time a new subgoal is generated it is compared with the list 64 and if it is found that the subgoal is already present, processing is terminated.

Certificates (and thus premises 54) may contain validity conditions that are not easily discharged, such as time ranges or online checks. This makes it hard to check these conditions either before or during proof so in the Figure engine validity is only checked once a trust chain has been located, this being done during a forward traversal of the chain. Of course, this means that an otherwise valid trust chain may have to be rejected. In this event, processing must be re-started to find another proof (there may be multiple proofs); to enable processing to continue where it left off, the state of the proving process at the time the first proof was found was stored in state memory 65.

The processing block 59, could alternatively be arranged to find all possible proofs at one go, these proofs being stored and one selected for validity testing, the other proofs not being used unless the first fails the validity check.

Operation of the Figure 6 engine will now be illustrated by two examples. The first example relates to the situation depicted in Figure 7. Resource R is set to allow access by Company X including by any employee of Company X provided they can prove this. Resource R trusts a principal K_{PUB_X} for any matter related to Company X including its internal organisation (Divisions and employees); the principal K_{PUB_X} is, in fact, associated with a head-office server of Company X. Company X includes a Division Y that has a server which is associated with a principal K_{PUB_Y}. The attribute "Division Y of Company X" is bestowed on the principal K_{PUB_Y} (the Division Y server) by K_{PUB_X} (the head-office server) through certificate C_{X-Y}. In like manner a principal K_{PUB_Z} associated with an employee Z of Division Y is bestowed the attribute "Member of Division Y of Company X" by principal K_{PUB_Y} (Division Y server) through certificate C_{Y-Z}.

Consider now what happens when employee Z wants to use resource R and establishes himself with R as the keyholder associated with K_{PUB-Z}. Employee Z presents certificates C_{X-Y} and C_{Y-Z} to R and R now uses the trust chain discovery engine 50 to find a trust chain authorizing employee Z to use resource R. Figure 8 depicts how the engine proceeds based on the target primary goal (issuer: SELF; subject: K_{PUB_Z}), the premises derived from

certificates C_{X-Y} and C_{Y-Z}, and the axiom that K_{PUB_X} can be trusted for all things relating to Company . The discovery process proceeds in two decomposition stages. The first decomposition generates a pair of subgoals:

$$<SELF \rightarrow K_{PUB\_Y}> \text{ and } <K_{PUB\_Y} \rightarrow K_{PUB\_Z}>$$

5   the second of which is justified by the premise based on C_{Y-Z}. The second decomposition decomposes $<SELF \rightarrow K_{PUB\_Y}>$ into subgoals:

$$<SELF \rightarrow K_{PUB\_X}> \text{ and } <K_{PUB\_X} \rightarrow K_{PUB\_Y}>$$

the second of which is justified by the premise based on C_{X-Y} whilst the first of which is justified by the axiom which trusts K_{PUB_X} for all matters concerns Company X.

10

The second example is based on the situation depicted in Figure 9 which is similar to that of Figure 7 except that now the principal K_{PUB_Y} (Division Y server) bestows the attribute "Member of Division Y of Company X" on employee Z by using the employee's name "John Doe" as the subject of the certificate concerned (C_{Y-jd}) rather than the principal K_{PUB_Z}

15   associated with employee Z. The name "John Doe" (or, more fully, K_{PUB_Y}. "John Doe") is associated with the principal K_{PUB_Z} by a name certificate C_{Name}. The trust chain discovery process (see Figure 9) therefore involves a further stage of decomposition in order to translate the subject K_{PUB_Z} of the primary goal into the name "John Doe" (this extra stage is the first stage carried out).

20

In the foregoing, the issuer inherently trusted by the discovery engine has been SELF where SELF is used merely as an internal designation. In fact, SELF could be a principal capable of issuing certificates in which case a trust chain can be determined as found, not only in the case where the outstanding subgoal is matched by an axiom, but also where the

25   outstanding subgoal is justified by a certificate-based premise 54. Furthermore, as previously noted, the trusted issuer, rather than being SELF, could have been some specifically identified principal inherently trusted by the discovery engine for matters including the attribute specified in the primary goal; in this case, the trust chain is determined to be complete when the outstanding subgoal including the trusted principal is

30   justified by a certificate (that is, matched by a premise 54). Where there are multiple trusted principals and it is not possible to identify upfront which will ground the trust

chain, the issuer of the primary goal can be specified generically (this could be by a null issuer as with the representation of SELF); during the discovery process each new outstanding subgoal is then checked to see if it matches with a premise having as an issuer any of the trusted principals. It will be appreciated that this latter approach is generally less

5 attractive than using SELF as the trusted issuer with axioms corresponding to delegations from SELF to the principals to be trusted, as already described.

In the foregoing examples, the engine 50 has been assumed to be associated with the resource R as depicted in general terms in Figure 11 - in other words, the requestor

10 (employee Z in the examples) merely sends to R all the certificates that Z thinks might be useful in establishing the trust chain and it is up to the requestor to prove that such a chain exists. It would alternatively be possible to associate a discovery engine with the requestor rather than the resource (see Figure 12), the requestor first determining a relevant trust chain and then sending only the relevant certificates, in the correct order, to the resource;

15 the resource then has a relatively simple task to reduce the certificates to prove that the requested is entitled to access. Of course, the requestor does not necessarily know the trust assumptions of resource R that can be used to ground a trust chain; accordingly, the requestor must first notify its requirements to the resource which then responds with advice as to what trust assumptions might be of use to the requestor in determining appropriate

20 certificates to send to the resource.

It will be appreciated that the described trust-chain discovery engine is not restricted to use with SPKI-like certificates since the 5- or 4-tuples used by the discovery engine are derivable from other forms of certificates as is explained and illustrated in section 6.5 of

25 RFC2693 (see reference 3)

The present engine uses linear search to find premises generating subgoals. It is possible to index premises by subject to focus the search. This would reduce the amount of work considerably when the premises set become large.

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Processing of Conditional Certificates by the Figure 6 Discovery Engine

The Figure 6 trust-chain discovery engine is also capable of handling certificates containing subject-directed conditions such as the attribute certificate shown in Figure 5. Where the Figure 6 engine finds that the decomposition of a goal involves a premise based on a certificate that contains a subject-directed conditional, it proceeds by introducing a

5 further subgoal to be proved corresponding to the condition included in the certificate. The further subgoal is of the general form that SELF has delegated the attribute specified in the condition concerned to the subject of the certificate. The inclusion of a further subgoal effectively branches the trust chain, both branches needing to be proved as will now be more fully described hereinafter with reference to Figure 13.

10

Where a conditional certificate includes multiple conditions in an AND relationship, then each condition gives rise to a new subgoal. However, if instead the conditions are linked by the OR operator, the engine 50 does not immediately generate a subgoal for each condition but starts by generating a subgoal for a first one of the conditions - only if the engine 50 is

15 unable to generate a trust chain for the branch depending from that subgoal does it consider the next condition by generating a corresponding subgoal which it then seeks to prove.

Figure 13 depicts the course of processing effected by the Figure 6 engine in proving a primary goal 71, here unspecified. In Figure 13 goals (including subgoals) to be proved are

20 represented by circles with the decomposition of a goal being depicted by dependent lines connecting to two or more subgoals. The subgoals chosen to fit certificate-based premises and therefore justified by those certificates are shown with a bar and the letter 'C' below; where a subgoal is found as justified by an axiom (thereby grounding the trust chain) the subgoal is shown with a double bar and the letter 'A' below.

25

In the Figure 13 example processing, two single-condition conditional certificates are involved in justifying the trust chain giving rise to a main branch B1 for the trust chain and two side branches B2 and B3; branches B1 and B3 ground in respective axioms whereas branch B2 connects back into the main branch B1. More particularly, goal 72 is

30 decomposed into subgoals 73 and 74, subgoal 73 corresponding to a certificate-based premise; the certificate justifying subgoal 73 is a conditional certificate giving rise to a

further subgoal 75. At this point the trust chain being built splits into branches B1 and B2, the branch including subgoal 74 being considered the main branch. Similarly, decomposition of subgoal 74 is also based on a premise derived from a conditional certificate and gives rise to subgoals 77-79 where subgoal 79 is the based on the condition

5   included in the certificate justifying the subgoal 77; a further branch B3 is thus formed off the main branch B1.

The engine 50 pursues with proving one branch at a time, the tracker 63 being responsible for tracking what branches are to be proved and where the engine has reached in the

10   proving process. In respect of the Figure 13 example, the engine 5 first proves branch B1, this branch grounding in a first axiom. The engine then seeks to prove the branch B3 (chosen because it was the last branch created). Branch B3 grounds in a second axiom. Finally, the engine seeks to prove branch B2. This branch is special in that it actually loops back into the main branch B1 - this results from decomposition of goal 83 generating a

15   subgoal that is identical to subgoal 80 (or is encompassed by it). Engine 50 is arranged to spot this and to treat its proof of branch B2 as finished (the branch grounding to the first axiom through subgoals already forming part of branch B1 of the trust chain.

Example situations leading to branches in the trust chain are as follows. The primary goal

20   to prove is that a principal (employee Z) is an authorised buyer of department Y of company X. The department Y is a purchasing department but only those of its employees that have particular qualifications are entitled to the designation of authorised buyer. One way of handling this is to bestow the attribute "authorised buyer of department Y" on all employees (that is, their associated principals) using corresponding certificates but to make

25   the certificates conditional on the subject having a specified qualification. The main branch in the trust chain relates to the delegation (with conditions not considered) of the authorised buyer attribute on X , this chain being for present purposes taken be, in the forward direction, SELF $\rightarrow$ X $\rightarrow$ Y $\rightarrow$Z. The engine 50, when decomposing the primary goal (SELF $\rightarrow$ Z, authorised buyer attribute), uses the conditional certificate for employee

30   Z and generates in addition to the usual two subgoals, a further subgoal corresponding to (SELF$\rightarrow$ Z, specified qualification attribute).

The specified qualification could be one issued by a third party N for which company X is not treated by the axioms of engine 50 as being trusted to prove; instead, engine 50 holds an axiom that party N is to be trusted in respect of all qualifications issued by it. In this case, the trust chain branch relating to the qualification can be grounded in the axiom relating to party N. This corresponds to the situation represented by branch B3 in Figure 13.

Alternatively, the specified qualifcation could be one issued by the training section TS of department Y of company X; in this case, the qualification branch of the trust chain has a subgoal (SELF $\rightarrow$ TS) which, assuming that a certificate (Y$\rightarrow$TS) has been presented, decomposes into (SELF $\rightarrow$ Y) and (Y$\rightarrow$ TS). The latter subgoal is justified by the certicate whilst the former corresponds to a subgoal that is already part of the main branch. This corresponds to the situation represented by branch B2 in Figure 13.

With regard to the loop check previously described (where engine 50 is arranged to check for duplicate subgoals by comparing each newly generated subgoal with those already in the subgoal list 64, and to terminate processing if the subgoal is already present), this check is refined for handling branches resulting from conditional certificates. More particularly, processing is not terminated if a newly-generated subgoal present in one branch matches with a listed subgoal in another branch - this will generally indicate that the branch being explored has merged back into another branch that has already been proved.

With respect to the forward traversal of the trust chain carried by engine 50 to check the validity of the chain with respect to the normal validity conditions (date/non-revocation/permission), where the trust chain involves branches, then the forward traversal is done branch by branch, starting with the main branch (the branched structure of the trust chain having been returned by block 61 along with the list of subgoals proving the chain).

Appendix

This Appendix forms an integral part of the preceding description and of the specification as a whole.

5   1. Certificate Inference Rules

SPKI certificates and the s-exp syntax are described in references [2, 3, 4, 6]. SPKI defines two inference rules for certificates, a delegation rule and a name-rewriting rule. The delegation rule combines two certificates, one issued by A to B and one issued by B to C to give a third certificate issued by A to C. The name-rewriting rule allows the subject name

10   of a certificate to be rewritten using a name certificate. The SPKI definition is relatively informal, and we formalize it below.

In defining the certificate inference rules we follow the SPKI convention of representing the contents of a certificate by a *5-tuple* with the following fields:

15
- **issuer** i: Public key (or its hash) of the certificate issuer.
- **subject** s : Identifies who or what the capability is issued to. A public key, key hash or object hash (or a name for one).
- **authorisation** a: The attributes (capabilities, authorisations, or other characteristics) transferred from the issuer to the subject by this certificate.

20
- **delegation** d: Boolean, if this is true the subject is allowed to delegate capabilities.
- **validity** v: A collection of conditions which must all be true for the certificate to be valid.

25   We use the following notation for a 5-tuple:

$$< i, s, a, d, v >$$

where i, s, a, d, v are the certificate parameters above.

We use the following notation for a name certificate:

30
$$[i.n = s, v]$$

with fields

- **issuer** *i*: Public key of the certificate issuer.

- **name** *n*: Name being defined.

- **subject** *s*: Name or principal the name is defined as.

- **validity** *v*: Conditions which must be true for the certificate to be valid.

5

We present goals in the form of *sequents*:

$$\Gamma \vdash A$$

Here Γ is a list of certificates, the *assumptions* or *premises*, while A is the resulting

certificate, the *conclusion*. The symbol $\vdash$ is called *turnstile* and is pronounced *entails*. The

10   inference rules are presented as a *sequent calculus* [5].

This is the **certificate delegation rule**:

$$\frac{\Gamma \vdash < s_0, s_1, a_1, T, v_1 > \quad \Delta \vdash < s_1, s_2, a_2, d_2, v_2 >}{\Gamma \cup \Delta \vdash < s_0, s_2, a_1 \cap a_2, d_2, v_1 \cap v_2 >}$$

15

This means that if the sequents above the line can be proved the sequent below the line

follows. Here $a_1 \cap a_2$ is authorisation intersection and $v_1 \cap v_2$ is validity intersection.

The rule requires that the subject of the first certificate, s_1 , is equal to the issuer of the

20   second certificate. It is possible for a subject to be a hash as well as an explicit principal,

and we consider a hash equal to a principal if the principal's hash is equal to it.

The **name certificate rule** is

$$\frac{\Gamma \vdash < i_0, i.n.y, a, d, v_1 > \quad \Delta \vdash [i.n = s, v_2]}{\Gamma \cup \Delta \vdash < i_0, s.y, a, d, v_1 \cap v_2 >}$$

25

Here we use *i.n* for a name starting with *i*. So the rule says that a name with a prefix

matching the definition can be rewritten by replacing the prefix with the value.

30   **Assumption rule:** $\dfrac{}{\Gamma, A \vdash A}$

A A

Adding   to a set of assumptions proves   .

Weakening rule:

$$\frac{\Gamma \vdash < s_0, s_1, a_1, d_1, v_1 >}{\Gamma \vdash < s_0, s_1, a_2, d_2, v_2 >}$$

5

as long as a_2; d_2; v_2 are respectively weaker than a_1, d_1, v_1 . For tags a_2 is weaker than a_1 iff (if and only if) $a_2 = a_1 \cap a_2$. For delegation flags d_2 is weaker than d_1 as long as d_2 is not true when d_1 is false. For validities v_2 is weaker than v_1 iff $v_2 = v_1 \cap v_2$.

10

Tag matching rules

The authorisation field (or tag) in a certificate can contain attribute/authorisation patterns as well as explicit authorisation. Also an explicit tag is compatible with any longer tag.
15   Tags have to be intersected as part of the verification process, and we define the tag intersection rules here. Abstractly we consider a tag as defining a set of objects matching it. Tag intersection is then set intersection, where the resulting set must be expressed using tags.

20   We define tag intersection as follows. Tag intersection is commutative, so a rule for x intersect y also applies to y intersect x. We always use the most specific rule. Any cases not covered are defined not to intersect.

- atom x – atom y: intersect if they are equal. The result is x.
- list x – list y: intersect if a prefix of one has elements that intersect the corresponding elements of the other. The result is the list of prefix intersections
25   appended to the remainder of the longer list. If there is no intersecting prefix they do not intersect.
- star – y : always intersects, with result y.
- set x – y: intersect if there is some element of x that y intersects. The result is the
30   set of all intersections of elements of x with y. If the result has one element it is returned instead of a set.
- set x – set y: intersect if there is some element of x that intersects some element of

y. The result is the set of intersections of elements of x with y. If the result has one element it is returned instead of a set.

- range x – atom y: intersect if y lies in the defined range. The result is y.
- range x – range y : intersect if they have the same ordering type and a non-empty intersection range exists. The result is the biggest range that is compatible with them both.
- prefix x – atom y: intersect if y has the given prefix. The result is y.
- prefix x – prefix y : intersect if their prefixes are compatible. The result is a prefix tag with the longer of the two prefixes.

Here, tags are defined not to intersect in some cases where the semantics intersect. Consider range–prefix intersection for example. This is defined to fail, but could be computed. The set tag is essentially a logical *or* of tag patterns. It might be useful to consider adding a logical *and* of tag patterns. This would make it simple to define arbitrary tag intersection: in the absence of a specific rule it would be the logical *and* of the tags.

Tags are equal if they have the same type and equal parameters, except for set tags. A set tag x is a subset of set tag y if every member of x is equal to a member of y. A set tag x is equal to a set tag y if x is a subset of y and y is a subset of x. Equality of set tags is independent of the order of their elements.

Semantically tags are the same if they express the same sets. The tag equality rule attempts to reduce this to syntactic tests on the tags. This means that tag equality fails in some cases where semantics are equal. It may be worth considering working out a complete tag equality rule based on the semantics. If a normal form exists we can reduce tag equality to equality of normal forms. If a normal form does not exist we require a satisfiability checker for the tag logic and this may be provided using a predicate tableau [1].

2. Backwards proof

Inference rules naturally suggest doing *forwards proof*, working from hypotheses to conclusions. However, here we do backwards proof by using them in the reverse direction

to decompose a goal into subgoals. We use the theorem-proving technique of *backwards proof* to derive the sequence [5] though we need to modify the rules to make this work. Consider the delegation rule. Working backwards we pick a_1 and a_2 equal to the tag in the goal, and use the same assumptions. We treat the other fields similarly.

5

$$\frac{\Gamma \vdash < s_0, s_1, a, T, v > \qquad \Gamma \vdash < s_1, s_2, a, d, v >}{\Gamma \vdash < s_0, s_2, a, d, v >}$$

where the rule is now to be interpreted in the reverse direction, telling us how to construct subgoals from the goal.

10

The name certificate rule is modified similarly:

$$\frac{\Gamma \vdash < i_0, i.n.y, a, d, v > \qquad \Gamma \vdash [i.n = s, v]}{\Gamma \vdash < i_0, s.y, a, d, v >}$$

We can use a *thinning* rule to drop assumptions:

15
$$\frac{\Delta \vdash A}{\Gamma \vdash A} \quad \text{if } \Delta \subset \Gamma$$

This gives us a more general assumption rule:

$$\frac{}{\Gamma \vdash A} \quad \text{if } A \in \Gamma$$

With regard to constructing a proof, running the delegation rule or name certificate rule

20 backwards would appear to produce two subgoals. However, if we always choose the second subgoal to be one of our assumptions we can discharge it immediately, leaving one subgoal. Given a goal we iterate through the assumptions looking for certificates that allow us to use one of the reverse rules. When we find a suitable name certificate we rewrite the subject using the inverse of the name definition and try that subgoal.

25

We examine certificates to see if they are suitable as the second premise in the delegation rule. They must have the same subject as the goal and authorize what it does. In practice we combine this with the weakening rule and accept certificates that authorize at least as much as the goal. It is convenient to ignore the goal's validity conditions at this stage as

30 they can be handled later by a forward proof traverse. The first premise of the rule becomes the subgoal. If proof of a subgoal fails we resume the iteration through the

assumptions looking for suitable certificates. If this backtracking runs out of alternatives the proof as a whole has failed. If the proof succeeds we return the last subgoal and the list of certificates that lead us to it. We then traverse this list constructing the forwards proof to get the final conclusion. We check that the authorisation of the original goal is weaker than

5   the authorisation of the conclusion of the proof, but we allow the validity to be different. This is because we only know we want the validity to evaluate to true, but we do not know what validity conditions certificates will impose, and we may not be able to check them during proof (since they may include online checks). The validity must be checked before the authorisation is enacted.

10

Termination and completeness

It is possible to construct sets of name certificates such that forwards rewriting does not terminate. A simple example is $[i.a = i.a.a]$. However, backwards proof terminates even in the presence of this definition since it can never make a name longer. It is still possible for

15   backwards proof to loop however. This happens if a sequence of rewrites creates the same subgoal again. The name certificates $[i.a = i.b]$ and $[i.b = i.a]$ form such a cycle (which also loops forwards). Looping can also occur because of delegation cycles.

We prevent looping by keeping a stack of subgoals and checking whether a subgoal

20   already exists before adding it. This also causes termination, since in order for the trust-chain discovery engine to fail to terminate it has to generate an infinite sequence of different subgoals. This is because an infinite tree with finite branching must contain an infinite branch. However our certificate sets are finite so there is no infinite derivation using them (as long as we work backwards).

25

It can also be shown that the backwards algorithm finds a derivation if one exists. Suppose a derivation exists. It must start with a trust assumption, use name certificates or delegation certificates and end with the desired goal. At each point in this derivation we have a goal with a certificate justifying its derivation from another certificate. The algorithm considers

30   all possible candidates for such steps, so it must find them if they exist. The algorithm backtracks over all possible steps, so it must find the derivation if it exists. Combining this

with the termination property above we see that the algorithm is complete (finds a derivation if one exists) and terminates. This means it is a decision procedure for goals.

Trust assumptions

5   So far the trust assumptions have not been mentioned. We represent a trust assumption as a 5-tuple with a null issuer. Since null issuers are illegal in certificates they can arise in no other way. When a trust-chain discovery engine creates the initial goal it sets the issuer to null. This means that only proofs starting from the trust assumptions will be accepted. The proof process does not need to treat trust assumptions specially.

10

3. Extension

Sequent calculi normally contain logical rules in addition to the structural rules we have defined. These can be used to represent intermediate deductions, such as the *cut rule*

$$\frac{\Gamma \vdash A \quad \Delta, A \vdash B}{\Gamma, \Delta \vdash B}$$

15

This allows a proof to be structured into lemmas, and provides a formal basis for storing previously proved theorems and using them in proofs.

At present the described trust-chain discovery engine only supports proving a single tag,

20   with a set of tags treated as having to prove them all. This is a restricted form of logical *and*. It is possible to extend the calculus by explicitly introducing logical connectives, such as *and* and *or*, together with their inference rules. This would allow us to treat proofs of (*set) patterns more flexibly than at present.

25

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